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Opportunities to Improve Diagnostics Performance Using Computer-Based Product Definition Models and Simulations

Robert M. Rolfe, Task Leader

Herbert R. Brown
Richard P. Morton
William R. Simpson

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PREFACE

This paper was prepared by the Institute for Defense Analyses (IDA) for the Office of the Director, Industrial Capabilities and Assessments, Under Secretary of Defense for Acquisition and Technology, under the task entitled Integrated Diagnostics and Improved Affordability for Weapon Support Systems. It fulfills the following objective: to review, analyze, and assess defense product definition models and simulations that are based on computer-aided design, manufacturing, engineering, and test capabilities for enhancing integrated diagnostics capabilities of weapon systems.

The following IDA research staff members were reviewers of this document: Dr. Alfred E. Brenner, Dr. Brian S. Cohen, Mr. Robert Dighton, Dr. Richard J. Ivanetich, LTG Peter Kind (Ret.), Dr. Danny L. Reed, and Mr. Vashisht Sharma.

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Introduction

The Director, Industrial Capabilities and Assessments, OUSD(A&T), tasked the Institute for Defense Analyses to assess opportunities for enhancing diagnostic performance and lifecycle support affordability of defense systems through use of computer-based product definition models and simulations (M&S). A variety of computer-aided or assisted design and manufacturing tools are considered in the study: Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer-Aided Engineering (CAE), and Computer-Aided Test (CAT) – CAx, for short. Integrated diagnostics provides the conceptual framework for the study. It represents a systems approach where integrating diagnostic elements creates a total diagnostic capability that outperforms individual support and maintenance tools operating alone.

Findings

New CAx-based capabilities are enabling more efficient development and implementation of diagnostics capabilities.

This study described a number of ways computer-based product definition tools may be applied effectively during product design to achieve higher levels of system diagnostic performance and supportability. The study team approached the analysis by identifying sets of functional activities (new diagnostic capabilities and needs) considered desirable for enhancing diagnostics performance and lifecycle affordability in each of five major integrated diagnostic element categories (see Table ES-1). The opportunities to enhance diagnostic performance described in this paper were assessed against these functional activities from the following four perspectives: product design, maintenance fault detection and isolation, critical problem assessment, and predictive and prognostic capabilities.

These study results summarized more than 30 opportunities where CAx-based M&S capabilities may be used to enhance diagnostic performance and improve lifecycle affordability.

Table ES-1. Areas of Opportunities for CAx-based M&S to Enhance Integrated Diagnostics

Integrated Diagnostics Elements	Functional Activities (Capabilities and Needs)
Status Monitoring and Built-In Test (BIT)	• Design For Testability • Automated BIT Design — Common BIT Design & Interface Hierarchy — Common Mechanical & Electrical Analog Sensor Interfaces • Near Real-Time What-Ifs and Screening • Fault Screening & Anomaly Simulation • Prediction Algorithms — BIT for Prognostics — Reliability Centered Maintenance — Condition Based Maintenance
Automatic and Manual Test Systems	• Automated Testability Analyses • Automatic Test Program Set Generation — Digital — Mixed Signal • Near Real-Time Simulation for Fault Detection • Near Real-Time Simulation for Fault Isolation • Analyze (unique) Test Probe Results via Simulations • Predict Parametric Levels • Minimize Testing
Technical Manuals	• 3-D Visualization & Photo-Realistic Rendering • Animated Illustrated Parts Breakdown • Improved Technical Manuals (interactive, 3-D animation) • Analyze Technical Manual Problems • Flexible Maintenance Strategies
Data Collection and Analyses	• Configuration Tracking • Design Feedback • Evaluate Design Options for Maintenance and Support • Parametric Data Recall • Failure Analyses • Change History • Maintenance Feedback
Training and Knowledge Support Tools	• Develop and Use Maintenance Simulators • Baseline for Knowledge Support Tools • Baseline for Smart Diagnostics Tools • Analyze Maintenance Training Problems • Conduct What-Ifs

Many of the same core functional activities needed to achieve effective integrated diagnostics capabilities are essential to effective Integrated Product and Process Development (IPPD) strategies.

The functional activities needed to achieve effective diagnostics performance tend to coincide with core functional activities needed to support IPPD strategies. This is not surprising, since major objectives of integrated diagnostics and IPPD strategies are very similar (e.g., to develop and deliver cost efficient systems that are reliable, supportable, maintainable, and meet operational availability and performance needs).

For the joint DoD/industry Simulation Based Acquisition (SBA) initiative to be successful, it must facilitate development, implementation and lifecycle support of essential integrated diagnostics functional capabilities.

Objectives of the SBA initiative are to enable IPPD from requirements definition and initial concept development through testing, manufacturing, and fielding; and to increase the quality, military utility, and supportability of systems development. Core functional activities needed to achieve effective integrated diagnostics also represent the same functional activities needed to meet IPPD. Therefore, these integrated diagnostics functional activities are also needed to address SBA initiatives.

Recommendation

Integrated diagnostics should be an identifiable portion of SBA implementation action plans, and the integrated diagnostics community needs to be a participant.

Roadmaps for implementing SBA should include action plans to apply CAx-based M&S to enhance integrated diagnostics. Core functional activities, strategies, and objectives of integrated diagnostics and DoD's SBA initiative are inextricably interwoven. Identified opportunities to improve diagnostics performance using CAx-based data and tools are directly applicable to both IPPD strategies and DoD's SBA initiative during all phases of weapons systems lifecycles.

1. INTRODUCTION

1.1 Purpose

The Institute for Defense Analyses (IDA) was tasked by the Office of the Director, Industrial Capabilities and Assessments, Under Secretary of Defense for Acquisition and Technology, to assess opportunities for using computer-based product definition models for enhancing diagnostic performance and lifecycle support affordability of defense systems.

The computer revolution of the seventies, eighties and nineties has played a dominant role in advancing automated and assisted design, manufacturing, and engineering capabilities; specifically related to CAx[1] technologies. The result is computer-based models describing geometric, physical interfaces and installations, behavioral, and manufacturing aspects of designs that may be easily shared across enterprises responsible for development, production, operations, support, potential modification, and eventual disposal. These CAx technologies have fostered the development of digital master models and methods for using digital models to predict dynamic response or operation of products over time (e.g., simulation). Given these advances, the objectives of this study follow:

- Assess opportunities for enhancing integrated diagnostics performance through the use of CAx-based product models and simulations,
- Develop strategies for using CAx-based product models and simulations for improving weapon system diagnostic performance, and
- Identify needs for CAx-based product models and simulations that will permit systematic evaluation of integrated diagnostics lifecycle and affordability benefits.

[1] The term CAx refers to a variety of computer-aided or assisted design and manufacturing functions: Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer-Aided Engineering (CAE), Computer-Aided Test (CAT).

1.2 Background

"A necessary step in the maintenance and repair process of weapon systems is investigating the nature or cause of hardware and software anomalies inhibiting normal operation. Integrated diagnostics represents a systems approach where integrating diagnostic elements creates a total diagnostic capability that outperforms individual support and maintenance tools operating alone. While specific benefits of robust integrated diagnostic capabilities will vary by application, reported benefits include greater operational readiness, improved systems confidence, improved availability, reduced maintenance work loads, and reduced lifecycle costs" [IDA 96]. From this perspective, the following definitions are intended to serve as useful background information.

System: "Any aggregation of related elements that together form an entity of sufficient complexity for which it is impractical to treat all of the elements at the lowest level of detail" [Kluwer 1994].

Test: "A signal, indication, or other observable event that may be a normal output of a system or be caused to happen" [Kluwer 1994].

Testability: "A design characteristic which allows the status (operable, inoperable, or degraded) of an item to be determined and isolation of faults within the item to be performed in a timely and efficient manner" [MIL-STD-2165].

Integrated Diagnostics: " A structured process which maximizes the effectiveness of diagnostics by integrating the individual diagnostic elements of testability, manual testing, training, maintenance aiding, and technical information" [Keiner 1990].

1.3 Study Scope

This study is applicable to CAx-based product data, where the products are mechanical, electro-mechanical, electrical, and/or electronic in nature and the products may represent any level of a hierarchy of systems, sub-systems, assemblies, to components. The CAx-based product data, by its very nature, represents a model that embodies the physical, mathematical, functional, or otherwise logical representation of the product.

The study will focus on CAx-based product models, and simulations using data from these models, as these may be applied to the development and use of integrated diagnostic capabilities for enhancing diagnostic performance and lifecycle support affordability of systems. Simulations applying CAx tools may involve complex analysis

capabilities such as stress and strain, dynamics, kinematics, thermodynamics, etc. The opportunities for applying CAx-based product models and simulations will be reviewed from four perspectives of diagnostic capability development and use. These four perspectives follow:

1. Development and use of diagnostic capabilities during product design.
2. Application of integrated diagnostics in maintenance processes for fault detection and fault isolation.
3. Engineering analyses of critical problems and faults.
4. Development and use of fault prediction and prognostic capabilities.

The ability to identify and diagnose failures is significantly impacted by what takes place during product design. It is during this period when the fundamental maintenance approach is designed, and maintenance training and materials to support diagnostics are developed. In addition, complex weapon systems require significant developmental testing, as well as operational testing of early prototypes of the system. These tests result in significant diagnostic and maintenance experiences that need to be incorporated into maintenance support, and in some cases, can lead to changes in the design of the weapon system and the maintenance and diagnostic tools.

During the operational phase of a weapon system's lifecycle, many failures occur that need to be repaired by maintenance technicians. They may have at their disposal all the maintenance tools and logistics infrastructure developed during each prior phase of the lifecycle. In addition to the ways CAx product data may be used in those tools, they also require occasional direct access to descriptions of the products. The CAx models and simulations would be of utility in these circumstances. Experience in maintaining the system may also lead to design changes in the product.

Some failures require more analysis than can be developed by maintenance technicians. These include safety issues that threaten the survivability of the weapon system or its crew, as well as repeated failures that severely impact the systems availability. In these cases, problem analysis is likely to involve the engineering team that designed and manufactured the system. Their use of CAx data should be obvious, but they might reasonably require additional analytic tools that use that data. These analyses frequently lead to design modifications aimed at preventing a repeat of the problem or improving the product's availability.

Today's CAx tools include some analytic capabilities for assessing long-term use of the product, such as assessing wear on moving parts, temperature change effects, metal fatigue, etc. These tools support analyses that predict likely sources of failures and allow the establishment of periodic maintenance cycles. Knowing which parts are most likely to fail most often can result in significant improvements in the reliability and maintainability of the product.

As these descriptions indicate, these four perspectives are not mutually exclusive. In fact, each one has impact on at least one other. It is this interdependency that offers possibilities for significant advantages from the integration of CAx product data into all facets of product support. While these perspectives may, and often do, overlap one another; they are useful categories in the context of this study for assessing opportunities for enhancing integrated diagnostics performance and lifecycle supportability of defense systems.

1.4 Approach

The approach selected for this study was intended to take maximum advantage of an earlier IDA study that investigated the *Adequacy of Mechanical-Based Technical Data in a New Defense Acquisition Era*. During the course of this earlier study, interviews specifically addressing CAx-based technologies were conducted with National Institute of Standards and Technology, South Carolina Research Authority, and major CAx suppliers. The IDA study team supplemented this previous work with information learned from literature searches, attendance and interviews with attendees of the 1998 International Workshop on System Test and Diagnosis[2] and 1998 Industry-Government Modeling and Simulation Crosstalk Conference[3], and telephone interviews with defense technical managers directly involved in integrated diagnostics related projects that are relying on CAx-based technologies.

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[2] 1998 Institute for Electrical and Electronics Engineering (IEEE) *International Workshop on System Test and Diagnosis*, Alexandria, VA, 7 - 9 April 1998.

[3] Sponsored by the George Washington Chapter of International Test and Evaluation Association (ITEA), Fairfax, VA, 20-21 May 1998.

1.5 Organization

Chapter 2, *Foundation for Change*, provides insight into the effects of the computer revolution on design, engineering analyses, and manufacturing; discusses recent defense policy changes influencing design and support processes; and provides a short discussion on two ongoing defense initiatives to advance the capabilities of modeling and simulation.

Chapter 3, *Opportunities for Enhancing Diagnostic Performance*, contains a summary of opportunities for applying CAx-based models and simulations to enhance integrated diagnostics performance.

Chapter 4, *Potential Limitations*, discusses potential near-term limitations that may inhibit using CAx-based models and simulations for improving diagnostics performance.

Chapter 5, *Findings and Recommendation.*

2. FOUNDATION FOR CHANGE

The following subsections provide insight into the effects of the computer revolution on design, engineering analyses, and manufacturing; discuss recent defense policy changes that are influencing the design and support processes; and conclude with discussions of two ongoing defense initiatives to advance the capabilities of modeling and simulation (M&S).

The foundations upon which future defense acquisition and support are based will influence opportunities and strategies for using CAx-based product models to enhance diagnostics performance. The authors of this paper provide a detailed analysis of this background material, because policy changes, events, and technology developments of the recent past are having such a profound effect on capabilities to design, manufacturer, and support complex systems.

2.1 Computer Revolution

The broad application of computers to the challenges of design, engineering analysis, and manufacturing is relatively recent. The continuing computer revolution that began in the 1970s has been the dominant factor in the growth of extremely powerful automated and assisted design capabilities. This growth may be addressed from several perspectives:

- Declining costs of Computer-Aided Design (CAD),
- Direct linkage between CAD and manufacturing, development of interactive graphics and modeling capabilities,
- Implementation of broad data sharing and networking capabilities, and
- Future expectations.

2.1.1 Declining CAD Prices

The use of computer graphics for engineering design began in the styling studios of the automobile industry more than 30 years ago [Wysack 96]. However, the computer assisted capabilities were not widespread in the 1970s and early 1980s, principally due to the high costs. A major obstacle to the widespread use of CAD systems in the early

1980s was high costs of graphic workstations, typically costing $50,000 to $100,000 each.

Consequently, in order to be cost effective, these CAD systems needed to help the designer to be more productive. By the early 1990s this changed and functionally equivalent personal computer (PC)-based CAD systems were available in the $12,000 range [Wysack 96]. Now there is even greater computing power at less cost, coupled with relatively low cost, commercially available, mid-range CAD systems. A recent article appearing in Computer Graphics World presents results of a benchmark study of five leading solid modeling programs priced below $6500. All five programs were viewed as serious contenders in the mechanical CAD arena with capabilities that would have cost $18,000 and up only 18 months ago in similar software packages [CGW JAN97 p. 29].

Another review found that "Prices of mechanical CAD systems have fallen 16 percent since 1995." The study compared prices by soliciting bids on 14 systems in five and 11-seat configurations, and included five years of software maintenance charges [CAD 97].

2.1.2 Direct Linkage to Manufacturing

The origins of Computer-Aided Manufacturing (CAM) began in the 1950s. The first prototype numerical-control (NC) machine tool for mechanical manufacturing was introduced at the Massachusetts Institute of Technology in 1952. This development was followed in 1954 by a symbolic language called APT (automatically programmed tool) and the first commercially available NC machine tools in 1957 [Kalpakjian 95, p. 1122 & 1130].

As the development of electronics systems has progressed, tools for circuit board and integrated circuit routing were introduced. A number of CAx-based electronic product data formats have emerged (e.g., VHDL, EDIF, GERBER), and are directly linked to manufacturing processes such as producing layouts, manufacturing and test fixtures.

With the growth of computer technologies and the introduction of CAD systems, the logical use of computers and computer technology to assist in all phases of manufacturing a product expanded. Today databases developed in CAD are stored and processed further by CAM systems into instructions for operating and controlling

production machinery, manufacturing processes, material handling equipment, and automated testing and quality inspection equipment [Kalpakjian 95, p. 1181].

2.1.3 Interactive Graphics and Modeling Capabilities

The advent of interactive computer graphics dates back to the early 1960s, with the development work of Ivan Sutherland at Massachusetts Institute of Technology. Because of high costs, widespread use did not occur until the mid-1970s and early 1980s. The display of complex objects before this time were both too slow and too costly due to the computational intensive operations required (e.g., data transformations of an object from a three-dimensional spatial coordinate system to the desired two-dimensional display screen rendering, with hidden lines and hidden surfaces eliminated or clipped) [Hodson 92].

From the late 1970s through 1988, techniques were all basically the same for modeling objects as solids (solid modeling); and various combinations of geometric entities were used to construct solid objects. "In the late 1980s, the term parametric solid modeling was applied to a product from Parametric Technology Corporation (PTC), which produced the first commercial example of what we call today parametric/relational (or dimensional-driven) solid modeling. By January 1994, there were at least seven significant dimension-driven and/or variational solid modeling systems in the marketplace, with more appearing every few months" [LaCourse 95, p. 8.1-8.2]. This new dimensional driven approach makes use of variables and constraints in the solid model generation and modification, and governs the operations by mathematical and topological relationships. Solid models have also become important to the electronic industry with the advent of two-sided boards, multi-layer boards, and multi-chip modules.

Solid models contain not only information about the shape of an object; they also provide an analytical model of the volume embodied by these shapes for mechanical items, and precise geometric information on routing and paths for connectivity for electronic items. "By employing spatially 'complete' models, solid modeling (SM) systems are able to apply computer power directly to the design of parts and assemblies rather than to lower-level details such as drawings" [LaCourse 95, p. 4.1]. Consequently, solid models provide great insight for engineering analyses such as mass properties, interference and assembly modeling, kinematics, proximity factors, electronic cross-talk, channel requirements, etc. With improved insight into mass properties of an item, new Computer-Aided Engineering (CAE) tools, that include embedded Finite Element

Analysis (FEA) capabilities, are vastly improving a designer's ability to assess and optimize design characteristics such as thermal, structural, stress and strain, etc.

2.1.4 Data Sharing and Networks

"Recent trends in network utilization and sharing of information are driving objectives that the CAD/CAM community has had for years. Specifically, interoperability and common core functionality are in the forefront of every CAD/CAM vendor's product development activities. This is now making the integration of applications possible through advanced interoperability of 'best in class' software for MRP (Manufacturing Resources Planning), PDM (Product Data Management), and CAD/CAM to name a few" [SME 97, p.9].

2.1.5 Expectations for the Future

Today "there is a definite trend toward commercially available software as opposed to internally developed" [SME 97, p. 9]. Two conclusions made by the Society of Mechanical Engineers (SME) CAD/CAM Roundtable study are as follows:

> "The increased use of distributed work across networks demands better interoperability between CAD/CAM systems and more standardization."
>
> "We are on the threshold of a quantum increase in the speed and interoperability of CAD/CAM applications as operating systems take advantage of hardware developments and core software becomes optimized" [SME 97, p. 9].

In a keynote address presented at the M/CAD Expo 97, Jim Medlock, Chairman and CEO of Intergraph Corp, characterized his view of what will represent the major CAx drivers for the next decade:

- Internet (and all WEB related technologies)
- Commercial Computer Operating Systems
- Commercial Computer Architectures
- Plug and Play Software
- Object Data Bases

While there are clearly other drivers for CAx (e.g., integrated circuits cost and performance curves for memories and processors, and the commercial demands for capabilities in other markets), wide agreement voiced by other speakers and attendees

provide a level of confidence that these drivers will have at least a near-term influence on the CAx industry.

2.2 Defense Acquisition and Support Policy Changes

Defense acquisition reform initiatives and the restructuring of the defense industry are part of a Revolution in Business Affairs (RBA) that is creating a new era for defense system acquisition and support. "The RBA includes: reducing overhead and streamlining infrastructure; taking maximum advantage of acquisition reform; outsourcing and privatizing a wide range of support activities when the necessary competitive conditions exist; leveraging commercial technology, dual-use technology, and open systems; reducing unneeded standards and specifications; utilizing integrated process and product development; and increasing cooperative development with allies.[4]" While the effects of RBA have not yet fully played out in actual practice, there are many indicators as to what the future policy trends may hold for the defense acquisition and support communities. The following sections address many of the significant changes.

2.2.1 Preferred Use of Performance Specifications

In his 1994 memorandum: *Specifications & Standards – A New Way of Doing Business*, then Secretary of Defense Perry established a new defense policy that called for greater use of "performance and commercial specifications and standards in lieu of military specifications and standards, unless no practical alternative exists to meet the user's needs" [Perry 1994]. Performance specifications are also referred to as form, fit, function, interface (F3I) specifications. While performance specifications are not new, the emphasis given them represents a significant departure from the past.

2.2.2 Emphasis on Commercial Items and Competition

Legislative actions have increased emphasis on the use of competition and assigned preference to the use of commercial-off-the-shelf (COTS) items. One of the principal effects of the Federal Acquisition Streamlining Act (FASA) of 1994 was increased emphasis and preference for use of commercial items. The legislation established a new definition for commercial items, established preference for the

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[4] Keynote address to International Test and Evaluation Association Modeling & Simulation Workshop, Las Cruces, NM, December 9, 1997, by Dr. Patricia Sanders, Director, Test, Systems Engineering and Evaluation, Office of the Under Secretary of Defense (Acquisition and Technology).

acquisition of commercial items, and exempted commercial item contracting from many laws and regulations (such as exemption for competitive purchases of commercial items from the cost and pricing data requirements of Truth In Negations Act - TINA) [ESI 95]. The Federal Acquisition Reform Act of 1995 (FARA) further expanded the emphasis on satisfying Government needs with commercial items through an expanded definition of commercial items, and a more robust commercial item exception to the requirement for obtaining cost or pricing data. These acts apply equally to non-electrical as well as electrical issues, assemblies and sub-systems.

2.2.3 Distributed Configuration Control

Secretary Perry's 1994 policy memorandum also stated: "To the extent practicable, the Government should maintain configuration control of the functional and performance requirements only, giving contractors responsibility for the detailed design" [Perry 1994]. This new policy, in conjunction with the preferred use of performance specifications and the increased emphasis on COTS items discussed in the previous two Sections, is intended to permit the repair or update of design configurations to performance specifications. Under these circumstances, both the repair and product update would be accomplished by contractors as a normal course of business. The benefits are also cited in the *Defense Standardization Program, Performance Specification Guide*: "The performance-based acquisition does not encourage the continuing reprocurement of the same item. It expects the Government to capitalize on the technical expertise and ability of the industrial community in order to procure products at continually improving levels of performance and reliability" [SD-15].

2.2.4 New Management Processes

In May of 1995, the Secretary of Defense mandated that the concepts of Integrated Product and Process Development (IPPD) and Integrated Product Teams (IPT) be used throughout the acquisition processes to the maximum extent possible. *Mandatory Procedures for Major Defense Acquisition Programs and Major Automated Information Systems Acquisition Programs* [DoD 5000.2-R] defines IPPD as: "A management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing and supportability processes. IPPD facilitates meeting cost and performance objectives from product concept through production, including field support. One of the key IPPD tenets is multidisciplinary teamwork through Integrated Product Teams (IPTs)."

The IPPD process is an outgrowth of concurrent engineering practices, and reflects a systems engineering approach based on sound business practices and common sense decision-making. "To reduce the costs associated with the integration of complex systems it will be essential for the functional members of an IPT (e.g., design engineering, manufacturing, logistics, product support) to understand the concerns of their counterparts and to identify a program's technical challenges as early as possible. Tools available to an IPT include standard, relatively inexpensive computer equipment, virtual prototypes, and simulations. Such resources can aid in the development of a shared vision of the proposed system and provide a means for understanding the complex interactions among the configuration items in the system design" [Sanders 97].

2.2.5 Minimizing Data Requirements

DoD's Continuous Acquisition and Lifecycle Support (CALS) program called for the deployment of an Integrated Data Environment (IDE) concept in 1994. Under this concept, the contractor retains data in the contractor's preferred IDE data formats, permitting DoD to obtain data if and only if, needed. [IDE 96] Under this strategy, integrating contractors for major defense systems will store and configuration control product data; and program offices, depots, and service field activities may access the information when needed. Variations of this initiative are now being applied across the Services, with near term benefits of reduced initial data costs for engineering documentation and technical data. Much of the engineering documentation and technical data are in electronic formats produced by CAx products.

2.3 Defense Modeling and Simulation Initiative

DoD implemented a new policy (DoD Directive 5000.59, Subject: DoD Modeling and Simulation Management) in 1994 that required the establishment of a management and administrative structure for improving the oversight, coordination, and communication of DoD modeling and simulation (M&S) issues. This policy established the Defense Modeling and Simulation Office (DMSO) and the DoD Executive Council for Modeling and Simulations (EXCIMS). EXCIMS is a general-officer-level advisory group on M&S, while DMSO is a full-time focal point for M&S activities.

Several activities preceded and were considered instrumental to the creation of this policy. A plan was approved by the Deputy Secretary of Defense in June 1991 to strengthen the use of modeling and simulation. This was followed by the Institute for Defense Analyses report, *A Review of Study Panel Recommendations for Defense*

Modeling and Simulation [IDA 92]. This IDA document reviewed 179 recommendations made by 25 separate study panels over a 16-year period. Then in March of 1993, the DoD Inspector General issued an audit report, *Duplication/Proliferation of Weapon Systems' Modeling and Simulation Efforts within DoD*, that highlighted DoD's inability to effectively and efficiently utilize models and simulations.

At present DMSO is leading a DoD-wide initiative to establish a common technical framework that will permit greater interoperability of all types of models and simulations. In the context of this initiative, DODD 5000.59 defines a model as "A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process;" and a simulation as "A method for implementing a model over time. Also, a technique for testing, analysis, or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model." The DoD Modeling and Simulation Master Plan (DoD 5000.59-P) calls for the common technical framework to include a High Level Architecture (HLA).

The initial definition of the HLA was sponsored by DARPA's Advanced Distributed Simulation program, and was transitioned to DMSO in 1995. The resulting HLA baseline definition was approved by the Under Secretary of Defense for Acquisition and Technology in September 1996. "The HLA is based on the premise that no one simulation can solve all the DoD functional needs for modeling and simulation. The needs of the users are too diverse. The technical complexity of needed implementation is beyond what has been shown to be possible today or is likely in the reasonable future to be handled in a single simulation. Further, with changing user needs, it is just not possible to anticipate how simulations will be used in the future or in which combinations" [HLA 97]. Instead, the approach is to think in terms of multiple simulations, constructed compliant with the HLA so that they may easily inter-operate, and be reused in a variety of ways.

Models and simulations may be used to support a variety of defense needs that range over a hierarchy from (a) product development and engineering, (b) engagement of products from one-on-one to many-on-many, (c) groups of systems in mission and battle scenarios, and finally, (d) theater or campaign analyses. Relative to this study, we are most interested in identifying opportunities for using computer-based product definition models for enhancing diagnostic performance and lifecycle support affordability of defense systems. This goal aligns closely with what is frequently considered the lowest hierarchy level, i.e., engineering.

2.4 Simulation Based Acquisition

"Simulation Based Acquisition (SBA) is the process by which simulation is incorporated and integrated throughout the functions of the acquisition of a weapon system; from concept exploration, through prototyping and design, test and evaluation, fabrication and production to deployment and finally operations and sustainment." This definition is quoted from a study report: *Study on the Effectiveness on Modeling and Simulation in the Weapon System Acquisition Process*, commissioned by Dr. Patricia Sanders, Deputy Director, Test, Systems Engineering and Evaluation, in August 1995, and published October 1996.

During this same relative period, Mr. Dan Porter, the Navy Acquisition Reform Executive requested assistance of the American Defense Preparedness Association (ADPA) in providing an industry perspective on the realities and promise of the application of Modeling and Simulation to Acquisition. The ADPA *Study on the Application of Modeling and Simulation to the Acquisition of Major Weapons Systems* was published 27 September 1996.

The National Defense Industrial Association (NDIA) conducted a workshop on Simulation Based Acquisition on 16-19 March 1998. The objective of the workshop was to produce specific recommendations on how industry and Government should proceed to achieve both near-term and long-term benefits of SBA. Results were available at the DSMO Industry Day in Washington, DC, 1-3 June 1998. In addition, on 16 March 1998, Dr. Jacques Gansler, the Under Secretary of Defense for Acquisition and Technology, signed the memorandum: *Modeling and Simulation in Defense Acquisition.* In this memo, he "endorsed a joint DoD/Industry initiative under the auspices of the Acquisition Council of the Executive Council on Modeling and Simulation to define a roadmap for the Simulation Based Acquisition initiative," with the goal of defining this SBA roadmap by October 1998.

Dr. Sanders, in the speech given for Dr. Gansler at the NDIA workshop [Sanders 98], stated: "The Defense Department envisions an acquisition process supported by the robust, collaborative use of simulation technology that is integrated across acquisition phases and programs. The objectives of Simulation Based Acquisition are to:

1. Reduce the time, resources, and risk associated with the acquisition process;
2. Increase the quality, military utility, and supportability of systems developed and fielded; and

3. Enable integrated product and process development from requirements definition and initial concept development through testing, manufacturing, and fielding."

There is evidence presented in all of the above discussions regarding SBA that M&S is being used effectively in the acquisition process. However, there remains concern that it is not being applied in an integrated manner across programs or functions. In the Simulation-Based Acquisition Workshop, Executive Panel Debrief Synopsis, 19 March 1998, the following observations were put forward: "Clearly a good roadmap is needed to articulate the necessary tools and structure for SBA. Where gaps exist we need to look at where the responsibilities are. We should not be willing to start action until we know precisely where the shortfalls are."

3. OPPORTUNITIES FOR ENHANCING DIAGNOSTICS PERFORMANCE

This section of the paper addresses opportunities for applying CAx-based product models, and simulations using these models, to enhance integrated diagnostics performance. The intent here is (1) to show that there are viable and workable concepts, and (2) to show that these concepts dovetail quite nicely with the foundations for change discussed in Chapter 2 of this paper. Some of the opportunities to be discussed are presently being realized[5]. However, the realization of enhanced integrated diagnostics performance may be hindered by gaps between necessary tool capabilities, limitations of in-place frameworks and infrastructure for SBA, and ineffective incentives and metrics for applying M&S during IPPD to meet diagnostic needs. In this context, this section partially addresses, at least from an integrated diagnostics perspective, the concern of the NDIA SBA Workshop, Executive Panel Debrief Synopsis (re-quoted here for emphasis):

> "Clearly a good roadmap is needed to articulate the necessary tools and structure for SBA. Where gaps exist we need to look at where the responsibilities are. We should not be willing to start action until we know precisely where the shortfalls are."

The opportunities for applying CAx-based product models and simulations will be reviewed from four perspectives of diagnostic capability development and use: (1) development and use of diagnostic capabilities during product design, (2) the application of integrated diagnostics in maintenance processes for fault detection and fault isolation, (3) engineering analyses of critical problems and faults, and (4) the development and use of fault prediction and prognostic capabilities. The review of opportunities for enhancing diagnostics performance will address how and when capabilities of integrated diagnostic elements are considered and applied from each of these perspectives.

The following five categories of integrated diagnostics elements will be included in this analysis. Because of some progress in integrating diagnostic elements and also

[5] There were clear acknowledgements in both the study chartered by Dr. Sanders and the ADPA M&S study that the use of M&S in acquisition is not new, and that a wide spectrum of M&S tools is being employed in every phase of complex systems development.

because of technology advances that have resulted in the combining and blurring of capabilities, the functional capabilities of each of these elements are not necessarily mutually exclusive. However, for the purpose of discussing opportunities for applying CAx-based product data M&S, they will be addressed separately.

- Status monitoring and built-in test (BIT),
- Automatic and manual test systems,
- Technical manuals (including interactive electronic technical manuals (IETM) and maintenance-aids),
- Data collection and analyses, and
- Training and knowledge support tools.

3.1 Development and Use of Diagnostic Capabilities During Product Design

The ability to predict and/or diagnose and detect failures is significantly impacted by what takes place during product design. It is during this period when the fundamental maintenance approach is designed, and maintenance training and materials to support diagnostics are developed. In addition, complex weapon systems require significant developmental testing, as well as operational testing of early prototypes of the system. These tests result in significant diagnostic and maintenance experiences that need to be incorporated into maintenance support, and in some cases, can lead to changes in the design of the weapon system.

Table 1 presents a summary of potential opportunities to apply CAx-based product data models and simulations, for the development and use of diagnostic capabilities during product design. This table is followed by a listing of comments relative to each of the opportunities presented in the table.

Table 1. Opportunities to Apply CAx-Based Product Data M&S to the Development and Use of Diagnostic Capabilities During Product Design

Integrated Diagnostic Elements	Functional Capabilities / Needs	Opportunities to Apply CAx-Based M&S	Comments
Status Monitoring and BIT	• Design For Testability (DFT) • Automated BIT Design — Common BIT Design & Interface Hierarchy — Common Mech. & Elec. Analog Sensor Interfaces	• Automated DFT tools and add-ons to CAx systems • Automated BIT design and evaluation limited by common and/or standard formats, interfaces, reporting schemes, and hierarchical implementation strategies.	(a) (b)
Automatic and Manual Test Systems	• Automated Testability Analyses • Automatic Test Program Set (TPS) Generation — Digital — Mixed Signal	• Evaluate testability and fault coverage • Automated development of test programs	(c) (d)
Technical Manuals	• 3-D Visualization & Photo-Realistic Rendering • Animated IPB	• Direct link of 3-D models to CAx-based data • Animated simulations integrated in electronic manuals	(e) (f)
Data Collection and Analyses	• Configuration Tracking • Design Feedback • Evaluate Design Options for Maintenance and Support	• Direct link to as-built and as-designed CAx-based data • Provide hooks for added value to CAx-based product data • Model the maintenance and logistics lifecycle support capabilities	(g) (h) (i)
Training and Knowledge Support Tools	• Develop Maintenance Simulators • Baseline for Knowledge support Tools	• Virtual product models for training and design evaluations • Foundation for rule-based and knowledge support tool evolutions	(j) (k)

Listing of Comments in Table 1:

(a) Design For Testability (DFT). DFT tools are used to support product designers by identifying testability issues and recommending corrective action alternatives. At best they are presently semi-automated; however, future opportunities include greater automation and direct linkage to CAx-based product data. General DFT concepts include: Rule of Thumb Guides, and Iterative Design Evaluation.

- Rule of Thumb Guides – The following items are just two examples of the many sound testability guidelines that could be integrated with CAx systems, and used by design teams as designs evolve:

  (1) Automate design checking software to assure electronic devices never go directly to ground; and alternatively, include a pull-down resistor in the path to ground. This will permit the use of test probes when or if needed.

  (2) Assure design includes common reset features. This will permit control of system states when testing. [Kluwer 94]

- Iterative Design Evaluation – Some of the DFT tools are more suited for evaluating completed early design prototypes, and recommending testability enhancements. Opportunities exist to automate the evaluation of CAx-based product data models against testability criteria (as well as the rules of thumb discussed above) during the design process. The following are two of many examples where this capability might be automated:

  (1) Assessments of fault ambiguity group size. This will permit the designer to introduce additional internal access points if desired.

  (2) Assessments of electronic observability and measurability at each component. This will permit designers to add or modify test methods when desired. [Kluwer 94])

- Post-design DFT analyzers such as TEAMS, STAMP, and AITEST[6] are only indirectly tied to CAD product data and require extensive manual

[6] Test Evaluation And Modeling System (TEAMS); System Testability And Maintenance Program (STAMP); Artificial Intelligence Test (AITEST).

intervention in order to evaluate testability and maintainability features. Future opportunities include the greater automation and direct linking to the CAx-based product data.

(b) Automated Built-In Test (BIT). The automatic linking of design tools that implement status (or health) monitoring features and BIT capabilities directly to CAx-based product data is severely hampered by the lack of common or standard formats, interfaces, reporting schemes, and hierarchical implementation strategies. Consequently nearly every BIT and health monitoring design concept is unique, with little or no design reuse. While there has been progress by the international standards bodies in this area, much more progress is needed. However, once these standards are implemented, the feasibility for automating the design and implementation of BIT and status monitoring features by direct linking to CAx-based product data will be greatly improved.

- While IEEE 1149.1 (Test Port Access and Boundary Scan) standardizes on the electrical interface for BIT test access ports at the integrated circuit level, it does not standardize on the response formats nor reporting schemes[7]. Therefore each implementation tends to be design unique. Furthermore, this standard only addresses digital BIT.
- IEEE 1149.4 addresses the analog signal, sample and hold features for BIT; however, automated design evaluation or direct linkage to product data models is also limited by a lack of standard formats, interfaces, reporting schemes, and hierarchical implementation strategies. IEEE P1226.13 (Parametric Data Logging) is currently in ballot and partially addressed this issue.
- While some processes for incorporating BIT features in hardware are automated (i.e., at ASIC chip levels), the creation of the tests, the test hierarchy schemes for diagnosing from chip to system levels, and the actual design of system BIT interfaces typically must be accomplished manually by the test engineer.

[7] The one exception is the RUN BIST (built-in self test) command.

(c) Automated Testability Analyses. Tools are typically linked to the topological information in the CAx-based data (i.e., WSTA, STAT)[8]. As a result, these tools rely on the connectivity information from the CAx models, and thus lack technology domain specific details. Opportunities for enhancing testability analyses and ultimately optimizing designs could be greatly enhanced by integrating additional CAx-based product data beyond the topology in future analysis tools (such as domain specific details and specific applied component characteristics).

- Analysis tools permit engineers to estimate the testability of the system or product by considering the electronic circuit topology. The goal is to anticipate potential testability problem areas that may be avoided in the final design. Some of these tools are relatively primitive and only assess coverage (i.e., range, accuracy, frequency response, etc.) of parametric stimulus and measurement requirements.
- Testability is the actual maintenance characteristics that provide the ability to observe system behavior under test stimuli. While some tools include information beyond topology, most testability analysis tools are based on topology, and therefore may miss actual testability deficiencies while inventing others that actually do not exist. [Kluwer 94]

(d) Automatic Test Program Generation (ATPG). The test program set (TPS) consists of an interface device that connects the unit under test (UUT) with the automatic test equipment (ATE), and the test program which is a sequence of tests and instructions typically implemented in software run on the ATE. The goal to automate test program generation from the CAx-based product data has been achieved for select classes of products and ATE. However, for most DoD depot and field use TPS needs, there still remains a substantial manual intervention and development participation by the test design engineer. A short discussion of different classes of products and ATE follows:

- Bed of nails ATE may be used in post-manufacturing applications of circuit cards to verify compliant product. The "nails" are sets of electronic probes that contact the circuit card at multiple locations (sometimes

[8] Weapon System Testability Analyzer (WSTA) is part of the Integrated Diagnostic Support System (IDSS), and System Testability Analysis Tool (STAT).

counting up into the hundreds). By providing electronic stimulus and measuring responses between individual probes, the test program set may determine the status of the circuit card. This type of ATE typically verifies proper continuity between electronic nodes and the proper functionality of installed components. This class of ATE has experienced some success in automating TPS development, and tends to avoid system level functionality tests that must consider the interaction of many electronic components.

- Complex ATE that test complete assemblies (e.g., circuit cards) and subsystems (e.g., black boxes, line removable modules) at their system electrical interfaces such as electrical cables and edge connectors are used extensively in defense applications. The test stimulus and measurement activities performed by these ATE must consider the interaction of multiple components, and a variety of system states that might exist when the UUT is in actual use. While there are some test program development support tools available that link directly back to the CAx-based product data, full automation of the test program development activities is not presently a reality. Capabilities are more advanced for digital testing than for mixed signal and analog applications. For example, some digital test development tools semi-automatically convert the CAx-based product data representation to a fault simulation representation (e.g., convert the actual gate level circuit, characteristically made up of individual components such as XOR, AND, OR, NOT, etc., to a mathematically equivalent circuit of NAND gates). From this standardized circuit representation, the tool may randomly generate test vectors and fault dictionaries. The results of this tend to be inefficient, but effective for fault detection when present. However, since the standardized circuit is mathematically equivalent at a functional level but not representative of the actual components and circuit topology, fault isolation capabilities are prone to error. In contrast, the automated capture, creation, and simulation of test requirements for relatively complex mixed signal circuits is just beginning to emerge. For example, the VTest Program is a research and development (R&D) project being conducted by the U.S. Air Force intended to show the feasibility of automating the development of tester resource description information to be used for performing virtual testing of mixed signal products. Also

noteworthy, IEEE P1226.11 (Test Resource Information Model) is presently in development by the IEEE.

(e) 3-D and Photo-Realistic Rendering. 3-D solid modeling technologies are dominating current CAx-based product models. The CAx-based solid model product data represents an actual analytical model of the item, and as such, the capability to display and even rotate a visual 3-D rendering constitutes a powerful capability needed for designing complex, multipart assemblies. It is now possible, once the design has been created, to virtually look inside it, to inspect it from different angles, and to virtually interact with the model. Furthermore, the technology produces realistic renderings that are approaching photograph quality, and these renderings even include reflections and back-lighting features. Many of these same or similar renderings, needed by the IPTs while adhering to concurrent engineering processes and practices, will be needed by maintenance technicians during product support and diagnostic trouble-shooting. Abundant opportunities will exist for integrating the photo-realistic renderings in electronic technical manuals which will be derived directly from the CAx-based product data.

(f) Animated Illustrated Parts Breakdown (IPB). Many of the CAx tools permit animation and rotation of assemblies and related sub-components. Some CAx tools currently permit the dynamic simulation of product assembly and/or disassembly. The future opportunities to use these new CAx-based capabilities in Interactive Electronic Technical Manuals (IETMs) and Portable Maintenance Aids (PMAs) are only limited by one's imagination.

(g) Configuration Tracking. The CAx-based product data provides a detailed analytical model of the as-designed product, and often includes insight to actual product characteristics that may be unique to the specific manufacturing processes used in manufacturing (e.g., automated CAD to CAM transitions). Consequently, these CAx tools provide an excellent source of detailed quantitative and qualitative data often needed for verifying the health and status of subsystems, assemblies, and components.

(h) Design Feedback. While not currently advertised as a feature of CAx-based product data, emerging Product Data Management (PDM) tools are beginning to integrate and configuration-control/manage enterprise-wide product information and status. As a result, these PDM tools represent a potential

method of adding value to the CAx-based product data as new information is learned. For example[9]:

> "Test is pervasive throughout the product lifecycle. At each stage of that lifecycle we test to be sure of design conformance, manufacturing conformance, operational suitability, and others. A large portion of test involves product description material that is best and most fully documented at the design stage. However, in the current applications, the information for product design is often re-created in many differing formats with some test information peculiar to the test scenario added to the new version."

This draft paper goes on to suggest that a solution appears to be the development of a "value-added" approach to capturing design and test information over a product lifecycle, and especially during the design phase. This practice is also referred to as "back annotate" by putting new information directly into the design file. New CAx and PDM integrated tools may provide an excellent opportunity for implementing this "value–added" approach.

(i) Evaluate Design Options for Maintainability and Support. An integral part of the design of any weapon system is ensuring that the system can be maintained. Some of the significant issues include:

- Can items that need frequent replacement, inspection, test be accessed quickly and easily, and without causing collateral damage?
- Can access panels, fasteners, or specific assemblies that may need to be accessed be easily reached, and is there sufficient clearance for efficient use of test, diagnostic, and maintenance tools?
- Can all replaceable assemblies (e.g., LRUs, SRUs) be removed and replaced with minimal difficulty?

These and other issues related to maintenance and support can be investigated by providing "hands-on" access to both Electronic Computer-Aided Design (ECAD) and Mechanical Computer-Aided Design (MCAD) models by maintainers as a regular part of the design review process for the system and each of its components.

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[9] Quoted from a draft paper by the International Electrotechnical Commission (IEC) Technical Committee 93, Working Group 7, Authors William Simpson, and Lee Shombert.

In addition to improving designs for maintainability and support, this capability is useful in evaluating maintenance plans, determining levels of maintenance repair and maintenance facility requirements. Practical applications of this capability may be used during the design phase by IPTs in trading-off costs and performance requirements.

(j) Develop Maintenance Simulators. The CAx models used by maintainers to evaluate designs for maintainability and support can also be used to train maintenance and support personnel on how to conduct diagnostic and repair processes. In addition, simulators could be developed to provide dynamic illustrations of the correct way to execute diagnostic and maintenance processes. Coupled with recent advances in modeling human performance, these simulators could generate video streams showing correct body position, correct motion, and proper sequencing of events in diagnostic and maintenance procedures. The following example is quoted from the October 1996, Computer Graphics World:

> "In addition to product-design applications, feature-prototyping tools are being used increasingly for computer based-training applications. Honda, for example, has begun developing models for its dealers. According to Emultek's Ron Sella, 'We've created a simulation of Honda's antilock braking system, which now has computers in three different spots. Honda will use this to better educate its mechanics, who have been fixing the symptoms [of the complicated ABS system] but not the problems themselves when they come up.' Honda hopes the training simulation will minimize the cost of repairs and increase satisfaction." [CGW OCT 1996]

From yet another perspective, the Army is moving increasingly to simulation to leverage flying hours, but the Apache simulation software available for training is 1 to 2 versions behind the operational Apaches. They are training on old versions, where if done right the simulation should be leading and being used to train for the new. Under circumstances such as this one, opportunities for benefits will apply to both the operators in terms of flight training proficiency, and maintainers in terms of maintenance training proficiency.

(k) Baseline for Knowledge-Based Support Tools. Knowledge-based tools capture, refine, and synthesize information; and in some cases derive new

knowledge about systems from the CAx databases, maintenance histories, and learned information. In other applications, knowledge-based support tools capture the knowledge of expert maintenance personnel so that their seasoned understanding can be made available to less experienced maintainers. These tools are very expensive to develop and require knowledge about the specific system based on years of experience with that system. In order to make such tools available earlier in the product history, it would be desirable to embed in the tools only generic knowledge about systems (more particularly, subsystems) of a particular type, and furnish the details about a specific system through CAx-based product data.

3.2 Application of Integrated Diagnostics in Maintenance Processes

During the operational phase of a weapon system's lifecycle, many failures occur that need to be repaired by maintenance technicians. They have at their disposal all the maintenance tools and logistics infrastructure developed during each prior phase of the lifecycle. In addition to the ways CAx-based product data may be used in those tools, they also require occasional access to descriptions of the products. The CAx models and simulations would be of utility in these circumstances. Experience in maintaining the system may also lead to design changes in the product.

Table 2 presents a summary of potential opportunities to apply CAx-based product data models and simulations for the application of integrated diagnostics in maintenance processes. This table is followed by a listing of comments relative to each of the opportunities presented in the table.

Table 2. Opportunities to Apply CAx-Based Product Data M&S to the Application of Integrated Diagnostics in Maintenance Processes

Integrated Diagnostic Elements	Functional Capabilities / Needs	Opportunities to Apply CAx-Based M&S	Comments
Status Monitoring and BIT	• Near Real-Time What-Ifs and Screening	• Near real-time capabilities limited (Historical evaluations and prognostic capabilities discussed in Tables 3 and 4 respectively)	(a)
Automatic and Manual Test Systems	• Near Real-Time Simulation for Fault Detection • Near Real-Time Simulation for Fault Isolation	• Simulation of proper functioning products • Limited opportunity for near real-time simulation of products with faults	(b) (c)
Technical Manuals	• Improved Technical Manuals (near real-time 3-D visualization, photo-realistic rendering, and interactive 3-D IPB action)	• Use IETMs and PMAs with embedded CAx-based data and simulations (Note – Table 1 addresses the development of capability for manuals)	(d)
Data Collection and Analyses	• Configuration Tracking, and Parametric Data Recall	• Direct link to as-built and as-designed CAx-based data	(e)
Training and Knowledge Support Tools	• Maintenance Simulators • Baseline for Knowledge Support and Smart Diagnostics Tools	• Train technicians on virtual products (Note – Table 1 addressed the development of maintenance simulators) • Limited direct link, CAx-based data needs to be supplemented with historical use data	(f) (g)

Listing of Comments in Table 2:

(a) Near Real-Time What-Ifs and Screening. To the extent that these functions may be simulated or presented as higher level abstractions of as-built or as-designed capabilities for proper functioning products, there exist some opportunities to apply the CAx-based models and simulations. Examples of this type of activity might include a compare process between observed BIT/status monitoring results and the simulations of proper functioning products under pre-selected scenarios. The benefit for this capability is questionable, at least for BIT, since by definition BIT should already be comparing observed behavior against expected nominally good behavior that was pre-coded within the BIT system when implemented by the system designers.

However, unless the product is very simple, there will exist (at least for the near-term) very limited opportunities to use CAx-based models or simulations in near real-time to address anomalous behavior. [The rationale for this will be discussed in more detail in paragraph (c).]

(b) Near Real-Time Simulation for Fault Detection. Similar to the conditions described in comments paragraph (a)-Table 2 above, there exist some opportunities to apply the CAx-based models and simulations of proper operating products. Under these circumstances, a fault is detected by online monitoring sensors when the actual product fails to mimic the results of the simulation. It is conceivable that future testing methods may begin to use this concept to implement some classes of functional product tests to detect faults.

(c) Near Real-Time Simulation for Fault Isolation. It may be possible to use CAx-based models to simulate a wide range of faults in order to determine which fault or combination of faults could reasonably produce the observed symptoms. However, there are two problems that limit opportunities to use CAx data in this way:

- The number of potential faults and fault combinations that would have to be simulated in any but the simplest systems would be far greater than could be simulated in a reasonable amount of time.
- Most simulations assume that inputs are within acceptable ranges and that combinations of events and inputs are logically acceptable. When faults

occur, however, this may no longer be true, and the results of the simulation may no longer be valid.

(d) Improved Technical Manuals. A significant opportunity from CAx-based M&S will come from the benefits of advanced technical manuals that will provide 3-D visualization, photo-realistic rendering, and interactive action. This will permit future manuals in the form of IETMs and PMAs to support the maintenance technicians' diagnostic and repair tasks. The opportunities to apply CAx-based data were discussed in the Table 1 Comments paragraphs (e) and (f).

(e) Configuration Tracking and Parametric Data Recall. Readily available CAx-based product data will assure critical information may be located and accessed by technicians when and where needed to support maintenance actions. Specific opportunities may be associated with the direct link to as-built and as-designed CAx-based data previously discussed in Table 1 Comments paragraphs (g), (h), and (i).

(f) Maintenance Simulations. Defense products are employing greater levels of design integration, shared functionality, and distributed function management. At the same time, technology improvements are increasing the reliability of the individual functional subsystems. Synergistically, the inherent reliability of the systems are staying relatively the same or increasing slightly; however, the reliabilities of the individual sub-system elements are increasing significantly. Consequently, maintenance technicians may rarely experience an opportunity to fix some classes of critical faults, yet must be prepared to rapidly correct these classes of faults when or if ever confronted with the problem. CAx-based product data provides an excellent opportunity to develop and implement virtual product training simulators. Training simulators may be used on a continuing basis or when needed to update technician proficiency for rare critical maintenance actions (e.g., just-in-time training). These future tools represent implementations of capabilities discussed in Table 1 Comments paragraph (j).

(g) Baseline for Knowledge Support and Smart Diagnostic Tools. Opportunities to make direct use of the CAx-based data for these types of tools may be limited (except as baseline information as discussed in comments paragraph (k), Table 1). However, new PDM tools may make it possible for the initial

CAx-based data to be supplemented with historical use data. Opportunities may increase for integrated diagnostics tools of the future to capture and learn using "value-added" data. The usefulness of CAx-based products may be enhanced if new product information is added as it becomes available.

3.3 Engineering Analyses of Critical Problems and Faults

Some failures require more analysis than can be developed by maintenance technicians. These include safety issues that threaten the survivability of the weapon system or its crew, as well as repeated failures that severely impact the systems availability. In these cases, problem analysis is likely to involve the engineering team that designed and manufactured the system. The use of CAx data should be obvious, but the engineering team might reasonably require additional analytic tools that use the CAx data. These analyses frequently lead to design modifications aimed at preventing a repeat of the problem or improving the product's availability.

Table 3 presents a summary of potential opportunities to apply CAx-based product data models and simulations to the engineering analyses of critical problems and faults. This table is followed by a listing of comments relative to each of the opportunities presented in the table.

Table 3. Opportunities to Apply CAx-Based Product Data M&S to the Engineering Analyses of Critical Problems and Faults

Integrated Diagnostic Elements	Functional Capabilities / Needs	Opportunities to Apply CAx-Based M&S	Comments
Status Monitoring and BIT	• Fault Screening & Anomaly Simulation	• Review and compare observed BIT and sensor histories to nominal values expected by CAx-based product data	(a)
Automatic and Manual Test Systems	• Analyze (unique) Test Probe Results via Simulations	• Apply CAx-based simulations of system elements to identify expected nominal parameters, and compare with observed	(b)
Technical Manuals	• Analyze Technical Manual Problems	• Analyze CAx-based models and simulation to compare and analyze adequacy of documented procedures	(c)
Data Collection and Analyses	• Failure Analyses • Change History	• Conduct stress and operational performance analyses of design • Compare design baseline to manufacturer updates and field reports	(d) (e)
Training and Knowledge Support Tools	• Analyze Maintenance Training Problems	• Apply Cax-based models and simulations to compare and analyze training adequacy	(f)

Listing of Comments in Table 3:

(a) Fault Screening. Presumably a record of recent BIT recordings and/or operational status monitoring records will be available for some period of time preceding a critical problem. The fault analysis process will typically include a review of observed pre-fault records and a comparison of these values with the nominal values expected by the CAx-based simulations. Opportunities may be available to use CAx-based simulations to conduct what-if analyses of specific fault causing situations in order to mimic observed BIT or sensor monitoring histories.

(b) Analyze (unique) Test Probe Results via Simulations. When standard or operational test program sets fail to isolate either the current problem or the root cause of the problem, an engineering team may be asked to conduct a more detailed diagnostic investigation. For example, the engineering team may conduct non-standard tests by probing circuit nodes for which anticipated nominal parametric performance levels have not been established. CAx-based simulations may prove beneficial in identifying likely test probe locations and predicting nominal performance parameters at non-typical test points.

(c) Identify Problems with Technical Manuals. Some problems are the result of a failure to perform maintenance tasks correctly. In some cases, this may be caused by ambiguities or other problems with the technical manuals used by the maintenance technicians. The CAx-based models and simulations may be very useful in analyzing the maintenance procedures described in the technical manuals to determine where these problems exist.

(d) Failure Analyses. Opportunities to apply CAx-bases M&S data for conducting various forms of system, sub-system and assembly stress analyses of the design are increasing. New tools are providing engineering teams with a means of identifying intermediate system states and stress conditions under any and all potential operational loads. For example, CAx-based product data models are directly linked to many simulation tools for analyzing mechanical loads, kinematics and dynamics of moving structural and articulating members, temperature and heat transfer properties, and electrical timing and capacitance. Nearly any failure mode has the potential of being modeled and simulated, restrictions include one's imagination and the relative costs of simulation versus real-life testing. As computing power and capabilities of

off-the-shelf analysis tools increase, the costs of simulations will likely continue to decline.

(e) Change History. Review of change history is essential during any post-problem analysis. If “value-adding” and/or back-annotating of CAx-based product data becomes widespread, possibly using new PDM tools, engineering teams may be able to automate reviews of manufacturers’ design updates, operational product history, and field reports.

(f) Analyze Problems in Maintenance Training. Just as problems in technical manuals may lead to poor maintenance practices, so can problems in the training received by the maintenance technicians. The CAx-based models and simulations can be very useful in identifying the parts of the training that may be unclear, ambiguous, or actually wrong.

3.4 Development and Use of Fault Prediction and Prognostic Capabilities

Today’s CAx tools include some analytic capabilities for assessing long-term use of the product, such as assessing wear on moving parts, temperature change effects, metal fatigue, etc. These tools support analyses that predict likely sources of failures and allow the establishment of periodic maintenance cycles. Knowing which parts are most likely to fail or have the potential to fail frequently, can result in significant improvements in the reliability and maintainability of products.

Table 4 presents a summary of potential opportunities to apply CAx-based product data models and simulations to the development and use of fault prediction and prognostic capabilities. This table is followed by a listing of comments relative to each of the opportunities presented in the table.

Table 4. Opportunities to Apply CAx-Based Product Data M&S to the Development and Use of Fault Prediction and Prognostic Capabilities

Integrated Diagnostic Elements	Functional Capabilities / Needs	Opportunities to Apply CAx-Based M&S	Comments
Status Monitoring And BIT	• Prediction Algorithms — BIT for Prognostics — Reliability Centered Maintenance (RCM) — Condition Based Maintenance (CBM)	• Adopt preventive maintenance strategies developed from CAx-based models and predictive simulations of life limiting factors	(a)
Automatic and Manual Test Systems	• Predict Parametric Levels • Minimize Testing	• Identify and evaluate new testing strategies that consider parametric trends and predicts remaining life • Adopt new testing algorithms that take into consideration use factors and operational histories to optimize testing strategies	(b) (c)
Technical Manuals	• Flexible Maintenance Strategies	• Develop and implement flexible preventive maintenance strategies that rely on CAx-based simulation and algorithms	(d)
Data Collection and Analyses	• Maintenance Feedback	• Implement capabilities to capture and apply feedback performance information and compare the actual data with predictive simulations	(e)
Training and Knowledge Support Tools	• Conduct What-Ifs	• Provide tools to project remaining useful life and/or potential degraded performance based on CAx-based simulations	(f)

Listing of Comments in Table 4:

(a) Prediction Algorithms. New CAx-based product model and simulation capabilities will permit designers to expand the current use of BIT and status monitoring from fault indication to problem/fault prevention. Future opportunities will include the use of BIT and monitoring capabilities to indicate changing life status. Simulations will be essential for implementing BIT and status monitoring strategies such as Reliability Centered Maintenance (RCM) and Condition Based Maintenance (CBM). For example, simulations may be used to identify indicators of changing health status, such as predicting parametric data trends resulting from periods of excessive stresses, or the changing performance of life limited assemblies.

(b) Predictive Parametric Levels. New CAx-based capabilities will permit designers to better understand the functional and parametric responses of complex systems or subsystems. Armed with this knowledge, test engineers will be able to adopt new testing strategies that evaluate trends and levels of performance under a variety of degraded performance states. The new testing strategies will not only identify and evaluate where and why faults exist, these new strategies will indicate sources of marginal performance. In the future, technicians will be able to diagnose and determine the full status of assemblies, and assure appropriate repair actions are initiated to return items to service only when assured the item has an acceptable service-life remaining.

(c) Minimize Testing. The combined advantages of back-annotated or "value-added" data, maintenance data collected in the form of use factors and operational histories, and the CAx-based product models will lead to adaptable automatic testing strategies. These adaptable strategies will permit test programs to automatically identify the most likely cause of problems and optimize fault isolation test strategies so as to minimize testing. Benefits will include improved diagnostic accuracy and reduced testing times. Furthermore, most of the items tested under these adaptable testing strategies will not need a full suite of embedded stimulus and measurement instrumentation. As a result many of the tests may be accomplished with a simplified or downsized suite of test instrumentation. An outgrowth of this may be new generations of test systems that are reconfigured for "just-in-time

testing", thus reducing costs and increasing test equipment transportability when desired.

(d) Flexible Maintenance Strategies. Preventive maintenance is predicated on having a sense of what is likely to need maintenance or corrective actions in order to preclude problems. Enhanced knowledge of use factors and operational histories have not been adequate to assure preventive maintenance alone will preclude critical anomalies. However, new product health monitoring capabilities may evolve if this enhanced knowledge is integrated via CAx-based simulations with results of status monitoring, BIT, and automatic testing information. Opportunities include the evolution of new flexible strategies for system maintenance predicated on optimizing maintenance activities around the immediate defense needs. For example, the optimum solution for one situation may result in lowest total maintenance costs without compromising safety; while in another situation, the optimum solution may result in highest assurance of reliability and availability. It is even possible for both of these extreme maintenance strategy examples to be desirable and in place during the same period (e.g., the first may be desirable for state side training and sustaining operations, while the second may be desirable during periods requiring high readiness alert such as exists in current policing actions).

(e) Maintenance Feedback. Predictive capabilities over systems' lifecycles must include the continuous collection and analysis of use factors, stress and strain operational performance, maintenance histories, configuration status and change histories, and a thorough knowledge of the design details. At some point, the systems' complexity will exceed practical limits, and this task will only be manageable with automated analysis and simulation tools. Early practical opportunities will include implementations that capture and feedback maintenance data and system performance history records, and compare this actual data with data from predictive simulations.

(f) Conduct What-Ifs. Tools dependent on CAx-based simulations will provide opportunities for maintenance technicians to assess remaining useful life and opportunities for system operators to assess mission success under conditions with degraded performance. Under extreme circumstances, planners may use the CAx-based simulation capabilities to evaluate and consider trade-off

alternatives resulting from some contingent of weapons at less than full mission capable status.

3.5 Changing Foundation and Integrated Diagnostics CAx-Based Opportunities

The tables in the previous sections discuss the opportunities for applying CAx-based product models and simulations from four perspectives of diagnostic capability development and use. These perspectives are not mutually exclusive. In fact, each one has the potential to impact others. This interdependency offers possibilities for significant advantages from the integration of CAx-based product data into all facets of product support. However, the opportunities to apply CAx-based models and simulations of weapons systems product data are not independent of the *Foundation For Change* discussed in Chapter 2.

Evolving CAx-Based Capabilities. CAx-based capabilities have been driven, in large measure, by the exponentially increasing performance levels of the microelectronic and computer industries. Several industry associations have roadmaps that predict this trend to continue[10], and the driving forces behind this trend are commercial consumer demands for greater core CAx capabilities. Of even greater significance, the core CAx capabilities needed to realize many of the opportunities presented in this chapter are commercially available as off-the-shelf CAx-base product data models, and simulations using these models.

Revolution in Business Affairs. The new era for defense systems acquisition and support is empowering IPTs to make sound business decisions and optimize the design, manufacturing and supportability processes. New CAx-based tools, with their 3-D product models and simulations of these models, are providing essential information to all of the team members simultaneously. The evolving CAx-based capabilities are key to achieving the multidisciplinary teamwork necessary to achieve the objectives of the new IPPD strategies. Finally, the opportunities and capabilities to characterize and balance benefits of enhanced diagnostic performance against other performance requirements has never been better.

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[10] Electronics Industries Association (EIA), *33rd Annual Ten-Year Forecast Conference of Defense, NASA, and Related Markets Electronic Opportunities (FYs 1998-2007),* October 1997; Semiconductor Industry Association (SIA), *The National Technology Roadmap For Semiconductors*, 1994; Integrated Circuits Engineering Corp (ICE), *Status 1997, A Report on the Integrated Circuits Industry*, 1997.

Models and Simulations in Defense Acquisition. A number of studies (discussed in Sections 2.3 and 2.4) have found that current development activities in both the commercial and defense sectors are making use of CAx-based capabilities. Fundamental issues put forward by these studies include: Does there exist untapped opportunities that may be realized by CAx-based technologies for increasing quality, military utility, and systems supportability; and how can defense acquisition communities realize the full benefits of these new M&S capabilities? Many of the opportunities discussed in sections 3.1 – 3.4 of this chapter have gone untapped in the past because of both an inability to visualize the benefits and the technical limits of earlier M&S capabilities. However, the new CAx-based technologies will enable IPPD to visualize and simulate capabilities, and then trade-off the benefits of potential opportunities through virtual testing and evaluation of alternatives.

Common Aspects of ID and IPPD/SBA. The taxonomy used in this study to discuss opportunities for applying CAx-based product models and simulations for enhancing diagnostic performance was selected to be directly applicable to integrated diagnostics elements at individual phases or points-in-time throughout a product's lifecycle. However, ID has much in common with IPPD and SBA, and many of the opportunities to enhance diagnostics performance discussed in Sections 3.1 – 3.4 apply equally to the objectives of IPPD and SBA. Common aspects and interdependent relationships of ID, IPPD, and SBA are discussed in the following paragraphs.

Each includes processes that integrate results of multifunctional activities, typically performed by different design, manufacturing, and support teams over product lifecycles. These common links are illustrated by the respective definitions that follow:

- "ID is a structured process which maximizes the effectiveness of diagnostics by integrating the individual diagnostic elements of testability, manual testing, training, maintenance aiding, and technical information." [Keiner 1990].
- IPPD is "a management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing and supportability processes." [DoD 5000.2R]
- "SBA is the process by which simulation is incorporated and integrated throughout the functions of the acquisition of a weapon system; from concept exploration, through prototyping and design, test and evaluation, fabrication and production to deployment and finally operations and sustainment." [Sanders 96]

Also, a common thread extends to both the reported and objective benefits of ID, IPPD, and SBA. The following quotes provide examples showing results of these processes in reducing lifecycle costs, enhancing systems availability and supportability, and improving military performance and utility:

- "While specific benefits of robust ID capabilities will vary by application, reported benefits include greater operational readiness, improved systems confidence, improved availability, reduced maintenance work loads, and reduced lifecycle costs." [IDA 96]
- "IPPD facilitates meeting cost and performance objectives from product concept through production, including field support." [DoD 5000.2R]
- "The objectives of SBA are to (1) reduce the time resources, and risk associated with the acquisition process; (2) increase the quality, military utility, and supportability of systems developed and fielded; and (3) enable IPPD from requirements definition and initial concept development through testing, manufacturing, and fielding." [Sanders 98]

4. POTENTIAL LIMITATIONS

In contrast to the many opportunities discussed in Chapter 3, there exist near-term limitations for improving diagnostic performance through CAx-based models and simulations alone. Many of the claims attributed to modeling and simulation tend to be anecdotal in nature.

The following quote comes from the executive summary of a study *(Technology for the United States Navy and Marine Crops, 2000-2035*) conducted by the Naval Studies Board (NSB), Panel on Modeling and Simulation, Committee on Technology for Future Naval Forces, published in 1997. This quote comes in a section labeled: *The Potential for Failures and Disasters* and follows after one titled: *Rich Opportunities for Modeling and Simulation.*

> It is an open secret, and a point of distress to many in the community, that too much of the substantive content of such M&S has its origin in anecdote, the infamous *BOGSAT* (bunch of guys sitting around a table), or stereotypical version of today's doctrinally correct behavior. Too many forecasts are extrapolating unreasonably from the Boeing 777 experience, and from M&S successes in weapon-system and small-unit training, to imagined M&S systems of extraordinary complexity. Recent failures such as the automated Denver airport baggage system and the Federal Aviation Administration advanced air-traffic control system suggest the difficulties associated with reliably modeling and engineering complex systems. [NSB 97, p.6]

Included as a part of the appendix of this NSB study is a case study of the Boeing 777 virtual engineering (VE) experience. "While the Boeing 777 experience is exciting for the VE enterprise, we should recognize just how limited the existing CAD tools are. They deal only with static solid modeling and static interconnections, and not–or at least not systematically—with dynamics, nonlinearities, or heterogeneity." [NSB 97 p.138] The case study went on to note the 3-D solid CAx models did not include any of the dynamic attributes of individual parts, and the electronics and hydraulics had to be simulated separately. Even with all of these powerful tools, Boeing still needed to construct a physical prototype (e.g., iron-bird) to evaluate the dynamics of the internal vehicle.

4.1 Status of CAD Capabilities

Modern mechanical CAD (MCAD) systems produce sophisticated 3-D solid models of geometric elements of a design, and critical bookkeeping products to represent the full compilation of individual elements in the designed product. These 3-D solid models are static and nonexecutable. Some CAx-based tools are available that permit users to analyze and manipulate models of these static elements or even combinations of these elements. In contrast, modern electrical CAD (ECAD) systems produce mappings of circuit nodes or interconnects, a hierarchical functional summary of circuits and circuit elements, nominal time-based simulations of circuits and circuit elements, and sophisticated bookkeeping products that tie this information together. However, several product representation capabilities for both MCAD and ECAD are incomplete or missing:

- "Multi-resolution modeling formalism. Typically, one wants to predict the performance of an overall system from the properties of its components. This has been done manually, but there exists no formalism to facilitate the ready aggregation or disaggregation of product behavior.
- Cross-domain consistency. It is unrealistic to think that there will be just one 'object' describing the behavior of a system or component. Members of different disciplines will have their own representations expressing those properties of interest to them. …
- Propagation of uncertainty. No matter how detailed, there is always some element of uncertainty in the description of a system or component. Individual disciplines have characterized these uncertainties fairly well. What has not been treated, however, is how uncertainties in the model of one discipline propagate when the model is used in conjunction with the model of another discipline." [NSB 97 p.175]

4.2 Technology Expectation

Cautious optimism should prevail. Many of today's CAx tools did not exist just a few years ago, and those that did were not as pervasively available on personal computers as they are today. While there may exist missing capabilities, in all likelihood according to Moore's Law[11], we can anticipate near-term computer technology advances that will help to fill the void of these missing capabilities.

[11] In 1965, Gordon Moore, then chairman of Intel Corp., noted that the number of transistors that could be packaged in each new generation of modern computer chips tended to double every 18 to 24 months.

Many of the missing capabilities needed to achieve the goals of the SBA initiative are directly applicable to modeling and simulating systems' fault tolerance, effects of stress and strain, reliability, and maintainability. Coincidentally, these same capabilities and knowledge gained from these capabilities are essential for integrating diagnostic capabilities to predict faults, detect and isolate failures, and perform maintenance.

While advancing computer technology has enabled the development of new capabilities, the recent growth of CAx-based capabilities has been fueled by the competitive demands of the users. Projections by the CAD communities are that this trend should continue as long as Moore's Law is valid – many predict the trend will continue for at least another decade.

5. FINDINGS AND RECOMMENDATION

5.1 Findings

5.1.1 Enabler of Integrated Diagnostics Capabilities

New CAx-based capabilities are enabling more efficient development and implementation of diagnostics capabilities.

This study described a number of ways computer-based product definition tools may be applied more effectively during product design to achieve higher levels of system diagnostic performance and supportability. Equally important, this study has shown that the CAx-based product definition data may be used to improve maintenance training, support capabilities, and diagnostic performance over systems lifecycles.

Many of the opportunities to improve integrated diagnostics through the use of CAx-based models and simulations can be at least partially exploited today, and, indeed, are already finding their way into selected DoD programs. For example, the Army's Crusader program is using CAx-based models and simulations to optimize maintenance tasks and parts distribution, and the Joint Strike Fighter is giving maintainers hands-on access to the CAx simulations to critique the design from a maintenance perspective. In both cases, they expect to continue to make use of those models and simulations in maintenance training and technical manuals.

New CAx-based tools are enabling enhanced integrated diagnostics implementation by permitting engineers to design and evaluate virtual models. These tools are reducing the time needed by engineering teams to create new designs, diagnose design limitations, and evaluate multiple design options in simulated operations and support scenarios. As described in this study, there exist numerous opportunities to enhance integrated diagnostics functional capabilities. The following list provides a few examples of functional activities that (1) are being enabled by new and emerging CAx-based capabilities, and (2) are enhancing both the designers' and maintainers' abilities to achieve desired levels of integrated diagnostics performance:

- Design for testability and automated testability analyses

- Automated built-in test (BIT) design and post-anomaly analyses
- 3-D visualization and photo-realistic rendering for evaluating options
- Near real-time screening and what-ifs of design and maintenance options
- Fault screening and anomaly simulations of design and support options
- Predictive algorithms and analyses for life limiting constraints

5.1.2 Common Core Functional Activities

Many of the same core functional activities needed to achieve effective integrated diagnostics capabilities are essential to effective IPPD strategies.

The functional activities needed to achieve effective diagnostics performance tend to coincide with core functional activities needed to meet objectives of IPPD strategies. This is not very surprising since the major core objectives of the IPPD and integrated diagnostics strategies are very similar. For example, most IPPD and integrated diagnostics strategies include the following major core objectives:

- To develop and deliver systems that are reliable (e.g., meet desired performance over extended periods of time).
- To develop and deliver systems and their support infrastructure that will achieve desired systems availability levels (e.g., assure system will be available if or when needed).
- To develop and deliver systems and related capabilities necessary for detecting, isolating, and repairing faulty conditions efficiently and cost effectively (e.g., assure system can be supported and maintained).
- To trade-off system lifecycle costs against design options such as performance capabilities, development and production needs, support infrastructure, operational objectives, and support and maintenance needs (e.g., assure system meets needs at affordable lifecycle costs).

IPPD strategies are intended to enhance communication between multiple disciplines, and to balance achievable design capabilities against desired system program office objectives (e.g., propulsion capability, weight, speed, range, schedule, costs). The

CAx-based product definition data M&S, and the enhanced ability to share M&S data, are helping to achieve these core objectives. Coincidentally, these core objectives are common to the functional activities identified for applications with good integrated diagnostics performance.

5.1.3 SBA Success Constraints

> *For SBA to be successful, it must facilitate development, implementation and lifecycle support of essential integrated diagnostics functional capabilities.*

A successful SBA strategy must take advantage of CAx-based opportunities for enhancing integrated diagnostics, address the needs of lifecycle support activities, and leverage all lifecycle activities off each other to the maximum extent practical. As indicated in the previous finding, successful IPPD strategies are dependent upon successfully achieving integrated diagnostics functional capabilities. However, the third objective of DoD's SBA initiative is to "enable IPPD from requirements definition and initial concept development through testing, manufacturing, and fielding." Therefore, the core functional activities needed to achieve effective integrated diagnostics represent the same functional activities needed to meet IPPD, and thus SBA strategies.

The study team found many of the general SBA and integrated diagnostics goals to be very similar and closely aligned. For example, the second objective of DoD's SBA initiative follows and makes specific mention of systems supportability while providing reference to continued attention through a products lifecycle: "To increase the quality, military utility, and supportability of systems developed and fielded."

Consequently, the benefits and opportunities for using computer-based product definition models and simulations to improve diagnostics performance and to achieve SBA objectives tend to be the same:

- To meet desired performance over extended periods of operation.
- To assure systems will be available if and when needed.
- To assure systems can be supported and maintained.
- To assure systems meet users' needs at affordable lifecycle costs.

5.2 Recommendation

Integrated diagnostics should be an identifiable portion of SBA implementation action plans, and the integrated diagnostics community needs to be a participant.

Roadmaps for implementing SBA should include action plans to apply CAx-based M&S to enhance integrated diagnostics. Core functional activities, strategies, and objectives of integrated diagnostics and DoD's SBA initiative are inextricably interwoven. Identified opportunities to improve diagnostics performance using CAx-based data and tools are directly applicable to both IPPD strategies and DoD's SBA initiative during all phases of weapons systems lifecycles. The following summarizes these opportunities by phases:

- Concept definition & product development will benefit by assessments of design options against potential operational stresses, and evaluation of design supportability characteristics and maintenance infrastructures.
- Maintenance, fault detection/isolation, and repair will benefit by guidance provided as well as actions recommended for returning failed items to operationally-ready status.
- Systems update and modifications will benefit by assessments of critical problems or reoccurring faults, and engineering analyses of specific corrective actions.
- Systems performance prognostics will benefit by fault prediction capabilities for assessing systems performance limitations and resulting maintenance needs under a variety of operational scenarios.

The application of CAx-based models and simulations to integrated diagnostics is an essential component of effective IPPD strategies and DoD's Revolution in Business Affairs. For SBA to be successful, it must take advantage of these CAx-based opportunities for enhancing integrated diagnostics, address the needs of lifecycle support activities, and leverage all lifecycle activities off each other to the maximum extent practical. This study has described numerous ways design and engineering data can be used to improve supportability during product design, as well as to improve maintenance training and diagnostic performance. The integrated diagnostics community needs to get deeply involved in the SBA initiative currently underway.

Many of the opportunities described earlier cannot be fully realized today without further development in one area or another. For example, the automatic generation of a complete fault tree from CAx model data requires advances in analytical algorithms as

well as further advances in computing power. In general, needed advances fall into the following areas:

- Modeling techniques
- Simulation algorithms
- Standards
- Cultural awareness of the opportunities

Some advances in modeling techniques and simulation algorithms are likely to come from applications needed by commercial industries, but modeling techniques and simulation algorithms specifically related to defective components are not likely to be explored by anyone unless the maintenance and diagnostic communities encourage it. This does not necessarily require direct DoD investment. It may be adequate to get enough people to demand such capabilities from today's tool vendors. If their perception of the market is large enough, they will build the tools.

The CAx industry is already talking about the need for standards to support virtual industries, and it is unlikely that there will be a need for any DoD-unique standards to support integrated diagnostics. Nevertheless, the diagnostic community would be advised to participate in the ongoing standards activities to ensure that the results are adequate for their purposes (e.g., IEEE standards being developed for built-in test).

IPPD strategies are aimed at getting multiple cultures to communicate. CAx-based models and simulations, and the enhanced ability to share information at near real-time as designs are being developed, are helping to achieve these communication objectives. A task that remains is to ensure that diagnostics is adequately represented on IPTs, and that those representatives are aware of the kinds of opportunities to borrow from, and contribute to, the development process outlined in this report.

Many gaps and missing capabilities needed to achieve SBA initiative goals are directly applicable to modeling and simulating systems' fault tolerance, effects of stress and strain, reliability and maintainability. These capabilities and knowledge gained from these capabilities are essential for integrating diagnostics to predict faults, detect and isolate failures, and perform maintenance. While many opportunities were not practical in the past, the realization of these opportunities is now enabled by emerging CAx-based modeling and simulation tools.

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6. AUTHOR(S)
Herbert R. Brown, Richard P. Morton, William R. Simpson, Robert M. Rolfe

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses (IDA)
1801 N. Beauregard St.
Alexandria, VA 22311-1772

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13. ABSTRACT (Maximum 200 words)
This paper reports on analysis of opportunities for applying defense product definition models and simulations (M&S) that are based on computer-aided design, manufacturing, engineering, and test (CAx, representing CAD, CAM, CAE and CAT) capabilities to enhance diagnostics performance and lifecycle support affordability of defense systems. Opportunities for applying CAx-based product M&S were reviewed from four diagnostic domain perspectives: Development and use of diagnostic capabilities during design, application of integrated diagnostics in maintenance processes for fault detection and isolation, engineering analyses of critical problems and faults, and development and use of fault prediction and prognostic capabilities. Viable concepts for applying CAx-based M&S capabilities to improve integrated diagnostic element capabilities for each of these diagnostic domains were identified. During the analysis, the study team noted the application of CAx-based models and simulations to integrated diagnostics is an essential component of effective integrated product and process development (IPPD) strategies and DoD's simulation based acquisition (SBA) initiative.

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